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Parsing the effects of reward on cognitive control

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Abstract

The effect of reward on cognitive control has been a topic of exponentially increasing interest and this spawned an impressive amount of empirical findings. Inspired by the theoretical framework of Berridge and Robinson (2003), we propose that the variability in observations can be framed by dissociating different reward components. Similarly, as cognitive control is an equally multifaceted construct, we believe it is important to differentiate certain forms of cognitive control behavior. In pairing reward components to particular forms of cognitive control, we propose that the hedonic aspect of reward promotes explorative behavior, the learning component of reward induces exploitative behavior, and the motivational component of reward engages anticipatory behavior. We discuss the available literature in light of this proposition and present some guidelines on how to dissociate these different components of reward and cognitive control.

Introduction

Understanding how reward modulates human behavior and information processing has been a core challenge for psychologists for decades. In recent years an increasing number of studies started to investigate the effects of reward on cognitive control as well. These studies demonstrated that reward modulates task switching, conflict adaptation, response inhibition, memory, visual search, proactive control, and so on. However, the direction of these results remains ambiguous. While most of these studies demonstrate performance benefits following reward, other studies have showed detrimental effects of reward on information processing. For instance, Hickey, Chelazzi and Theeuwes (2010) showed that rewarded stimulus features capture attention even when counterproductive. Moreover, contradictory reward-based modulations have been described. For instance, while Braem, Verguts, Roggeman, and Notebaert (2012) observed increased conflict adaptation (see also Braem, Hickey, Duthoo, & Notebaert, in press; Stürmer, Nigbur, Schacht, & Sommer, 2011), van Steenbergen, Band, and Hommel (2009, 2012) observed decreased conflict adaptation following reward. It should be clear that we are currently in need for a new framework; a point that has also been raised in recent review articles by Chiew and Braver (2011) and Dreisbach and Fischer (2012). In this chapter, we provide such a framework on the basis of a proposition by Berridge and Robinson (2003).

A decade ago, Berridge and Robinson (2003) proposed parsing reward into three different components: a hedonic, a motivational, and a learning component. The affective or hedonic component of reward refers to the general positive feeling people experience when they receive reward. The motivational component of reward relates to increased (cognitive) effort people display when reward is promised for good performance. The learning component of reward refers to what learning psychologists call *reinforcement.* It results in an increased likelihood of observing the behavior that led to the reward. Recognizing that reward signals consist of different components was an important first step in understanding the complex effects of reward. Additionally, it reveals that the study of reward brings together three major fields of contemporary psychology: affective, motivational, and cognitive.

We will argue that to understand the effects of reward on cognitive control, a similar distinction should be made. We will dissociate explorative, exploitative and proactive control components. Once this distinction is made, a pattern starts to emerge and one can link each reward component to one specific cognitive control component. We will argue that the hedonic reward component activates explorative control processes, that the learning component promotes exploitative control processes, and the motivational component engages proactive control processes. Last, we will offer some preliminary guidelines on how these different components and their interactions can be disentangled and investigated.

Parsing reward

In general, psychologists seem to agree that reward is not a unitary concept but they seem to disagree on *how* to parse it. Here, we adhere to the idea of looking at reward in terms of three distinguishable psychological components: affective, motivational and learning (Berridge & Robinson, 2003).

The *affective* component is often referred to as the *hedonic* aspect of reward. Berridge and Robinson also call this component the 'liking' component. It involves opioid neurotransmission onto GABAergic neurons in the nucleus accumbens and, contrary to traditional assumptions, is unlikely to be mediated by dopamine. Whereas microinjection of opioid agonists increased facial liking reactions to sweetness (Pecina & Berridge, 2000) dopamine agonists do not change this (Wyvell & Berridge, 2000). The affective value of reward signals is most likely triggered by signals that enhance the inherently positive feeling associated with reward. In human experimental studies, this is typically accomplished by presenting affective pictures, emoticons or smiling faces. Positive affect can be triggered by the delivery of reward, but also by the anticipation of reward.

The *motivational* (wanting) component of reward is primarily activated when a cue informs participants that the following trial(s) can be rewarded when performed successfully. This is referred to as cue-triggered wanting. Rewards that are liked are also wanted; both components are therefore often co-activated. However, pharmacological manipulations demonstrated that the two components are dissociable. Manipulations of the dopamine network affect motivated behavior but not the liking

response (Berridge, 2007). The motivational component includes an extensive network with the accumbens, amygdala, basal forebrain and cortex. This component is also involved in addictive behavior (e.g., the incentive sensitization theory of addiction, Robinson & Berridge, 2008).

While it is fairly easy to assess the emotional state of participants in various conditions, measuring the motivational state is more difficult. Motivational effects are typically 'recognized' by means of changes in behavior. For instance, when participants respond faster in a particular task, or when they make fewer errors, it is interpreted as a motivational effect. Some studies do not present actual cues, but deliver reward only to a particular subset of stimuli. In those studies, the stimuli themselves act as a reward cue. For instance, Krebs, Boehler, and Woldorff (2010) associated reward to two out of four colors in a Stroop task. Stimulus color thus acted as a reward cue motivating participants to enhance performance. In this volume, Krebs, Hopf and Boehler describe similarities and differences between cue-based and stimulus-based reward effects.

Reward also has a *learning* component. This was initially captured by behaviorists, in interpreting reward as a positive reinforcer. A positive reinforcer is a stimulus that is presented after an action and has the effect that the action is more likely to re-occur (aka Thorndike's law of effect, Thorndike, 1911). Today, this principle lives on in the research field of 'reinforcement learning' which – inspired by these century-old theories – is devoted to the development of computational models of machine learning and neuroscience. The central idea of reinforcement learning is that agents are learning how to behave so as to maximize reward. The maximization of reward is the only goal that is implemented. In contrast to other computational approaches, the agent is not instructed what will be rewarded, but must discover what actions are rewarded (learning from interaction). One of the most intriguing aspects of reinforcement learning is the balance between exploration and exploitation. In order to maximize reward, the agent must exploit actions that were rewarded in the past, but in order to find potentially higher rewards, the agent must also explore the environment (Sutton & Barto, 1998). This balance, also referred to as stability versus flexibility, is also recognized as a crucial aspect of cognitive control (Cohen, McClure, & Yu, 2007).

It is important to stress that reward signals will often activate all components but the relative weight of each component will depend on the nature and context of the reward

signal. Before we discuss the effects of reward on cognitive control, we will first briefly introduce various aspects of cognitive control.

Parsing cognitive control

Broadly defined, cognitive control is the psychological function that keeps track of changing task-demands in order to adjust information processing accordingly. This function is studied in task-switching, congruency tasks, decision making, stop-signal paradigms and so on. Although cognitive control is often described as a unitary function, we believe that for understanding the effects of reward thereon, it is crucial to dissociate different forms of cognitive control. In order to keep information processing optimally adjusted to the environment, different types of control processes are required. Imagine writing a book chapter with a world championship soccer game playing in the background. When you hear the commentator raising his voice, it will be harder for you to focus on your writing. However, when you are highly motivated, you can increase selective attention and ignore the auditory irrelevant information. This adjustment of selective attention serves to increase stability and is often described as goal shielding. In reinforcement learning terms, we could say that this type of process serves exploitation of the environment. However, it is also possible to deliberately keep the television on to simultaneously stay informed about exciting game situations. In this case, cognitive control processes are required to increase flexibility, or exploration. For this, we can rely on reactive control processes (e.g., reactive upon the commentators raised voice, or the book chapter's content). However, cognitive control can also operate in a proactive way: by anticipating a difficult paragraph or a deciding penalty shootout, we can proactively change our attention accordingly. This distinction between reactive and proactive control is well captured by the dual-mechanisms of control (DMC) framework of Braver (2012).

Exploitation is a term borrowed from reinforcement learning. It describes behavior where agents repeat actions that have been rewarded in the past. This behavior is served by a psychological function that goes by many different names; selective attention, interference suppression, goal shielding, and so on. Although each of these functions is studied in specific paradigms, they all investigate how participants keep their focus on task-relevant information and increase stability. We consider conflict

adaptation as a prototypical example of this type of cognitive control behavior. Conflict adaptation is typically studied in congruency tasks like the Simon, the Stroop, and the Eriksen flanker task (Stroop, 1935; Simon & Rudell, 1967; Eriksen and Eriksen, 1974). In the Stroop task for instance, participants have to name the ink colour of a word, ignoring the meaning of the word. In this task, congruent stimuli (GREEN in green ink) are faster responded to than incongruent stimuli (RED in green ink). When the congruency effect is calculated separately for trials following congruent and incongruent trials, we observe a smaller congruency effect after incongruent trials than after congruent trials. This conflict adaptation pattern, also called the Gratton effect (after Gabrielle Gratton, who reported this effect for the first time), or the congruency sequence effect, presumably reflects increased task focus after encountering difficulties on an incongruent trial (Gratton, Coles & Donchin, 1992). Verguts and Notebaert (2008; 2009) provided a computational explanation for this behavioral pattern, which is of particular interest to the present work, because it relies on reinforcement learning principles. Without going into too much detail, the model uses the detection of conflict as a learning signal, in order to increase (active) task-relevant associations, thereby exploiting the behavior that led to successful conflict resolution. Note that this model was developed to capture various cognitive control effects in terms of general reinforcement learning principles.

Exploration on the other hand is behavior intended to find new and potentially higher rewards. This requires keeping an eye open for opportunities, and hence, processing more (irrelevant) information. While cognitive stability or exploitation is often beneficial in the above-described single conflict tasks, it can interfere with efficient task performance in other paradigms, such as task switching experiments (as demonstrated by Goschke, 2000; Brown, Reynolds, & Braver, 2007), where an exploratory mode can be more advantageous. In task switching studies, participants receive two different task goals. For instance, in a magnitude/parity task-switching experiment participants have to respond to the magnitude of a number whenever it is presented in green (< 5 press left; > 5 press right), and a parity task when the number is colored in blue (odd press left; even press right). Explorative behavior will result in smaller task-switch costs because participants keep a wide attentional focus, making them better prepared for task alternations.

Like exploitation and exploration, *anticipation* is another type of cognitive control behavior. The psychological function is referred to as proactive control, as opposed to reactive control processes. In the *dual mechanisms of control* model, reactive and proactive control *modes* are distinguished (Braver, 2012). Whereas reactive control reacts to stimuli, proactive control anticipates the onset of stimuli. Proactive control is typically investigated in cueing paradigms, but expectations can also trigger anticipatory behavior (e.g., Duthoo, Abrahamse, Braem, & Notebaert, 2013; Duthoo, De Baene, Wühr, & Notebaert, 2012). Anticipatory processes can induce exploitation and exploration. In a task switching study, for instance, a task cue indicating that the same task will be repeated will increase stability, while a task-switch cue will trigger flexibility.

We propose that cognitive control serves explorative, exploitative and proactive behavior. However, this is not the first time that the diversity of cognitive control was recognized. Baddeley and Hitch (1974) proposed that working memory includes three components. In addition to two slave components specialized for the maintenance of phonological information (phonological loop) and visuospatial information (visuospatial sketchpad), there is a central executive controlling cognitive processes. Inspired by this model, Miyake et al. (2000) distinguished mental set shifting, information updating, and monitoring and inhibition of prepotent responses as three separate functions. Notably, these models are inspired by a modular view of the brain, stressing the functional specialization of specific brain structures. We propose a distinction based on cognitive strategies, rather than specific control components or functions. Importantly, our approach is only meant to complement, rather than re-evaluate the framework presented by Miyake. In fact, it is best to see the present categorization between different cognitive control strategies, as one that can subsume or differentially recruit some of the more specific functions proposed by Miyake and colleagues (2000). For example, exploitation can involve functions like inhibition and information updating, while exploration might involve functions like set shifting and information updating. Distinguishing between these two types of categorization is also elucidating when it comes to the unity or diversity debate. While cognitive control clearly depends on a diversity of specific control functions, most strategies often require a combination of processes.

In the framework we present here, we dissociate three types of cognitive control processes, or three control components; exploitation, exploration and anticipation. Interestingly, in doing so, a natural match occurs with the above-described components of reward. In the following section, we will describe how the motivational component of reward recruits anticipatory control processes, how the hedonic reward component promotes exploratory control processes, and how reward-based learning relies on exploitative control processes (see Figure 1).

Parsing the effects of reward on cognitive control

Several recent studies tried to investigate the influence of reward on cognitive control, but the results remain equivocal and call for a better conceptualization and dissociation of reward schedules (see also Chiew & Braver, 2011; Dreisbach & Fischer, 2012). Specifically, while some studies focused on block-wise effects of reward schedules (e.g., Locke & Braver, 2008), others investigated the effects of random reward cues preceding the trial to indicate if a trial can be rewarding or not (e.g., Padmala & Pessoa, 2011). Alternatively, other studies have looked at the influence of item-specific reward on conflict processing (e.g., Krebs, Boehler, & Woldorff, 2010), while yet another group of studies used designs where reward signals were not cued, but only followed performance, either performance-contingent (e.g., Stürmer et al., 2011), or not (e.g., van Steenbergen et al., 2009). These precise reinforcement schedules aside, different types of reward signals have been used as well. While some used monetary gains denoted by (relatively) abstract symbols (e.g., Braem et al., 2012, 2014; Krebs, Boehler, & Woldorff, 2010; Hickey et al., 2010; Padmala & Pessoa, 2011; Stürmer, Nigbur, Schacht, & Sommer, 2011), others used inherently affective smileys or affective pictures (Braem et al., 2013; van Steenbergen et al., 2009; 2012). It is likely that the former promoted motivational or learning components of reward, while the latter predominantly activated the hedonic aspect of reward. Lastly, these studies also differ in the behavioral measure of interest. While some mainly focus on exploitative behavior (e.g., van Steenbergen et al., 2009), others targeted explorative behavior (e.g., Kleinsorge & Rinkenauer, 2012), and yet others focused on proactive anticipatory behavior (e.g., Chiew & Braver, 2013).

Although there are a substantial number of small differences between all these experiments, we believe a broad distinction can be made by using the framework introduced earlier. Therefore, in what follows, we will try to illustrate how these experimental designs have variously targeted one of the above-mentioned three reward components, by highlighting their differences in reward schedules, reward types, and cognitive paradigms. We will first discuss each of these three reward components in turn, along with their associated cognitive control behavior (see Figure 1). In the subsequent section we will outline some first guidelines on how to dissociate between them.

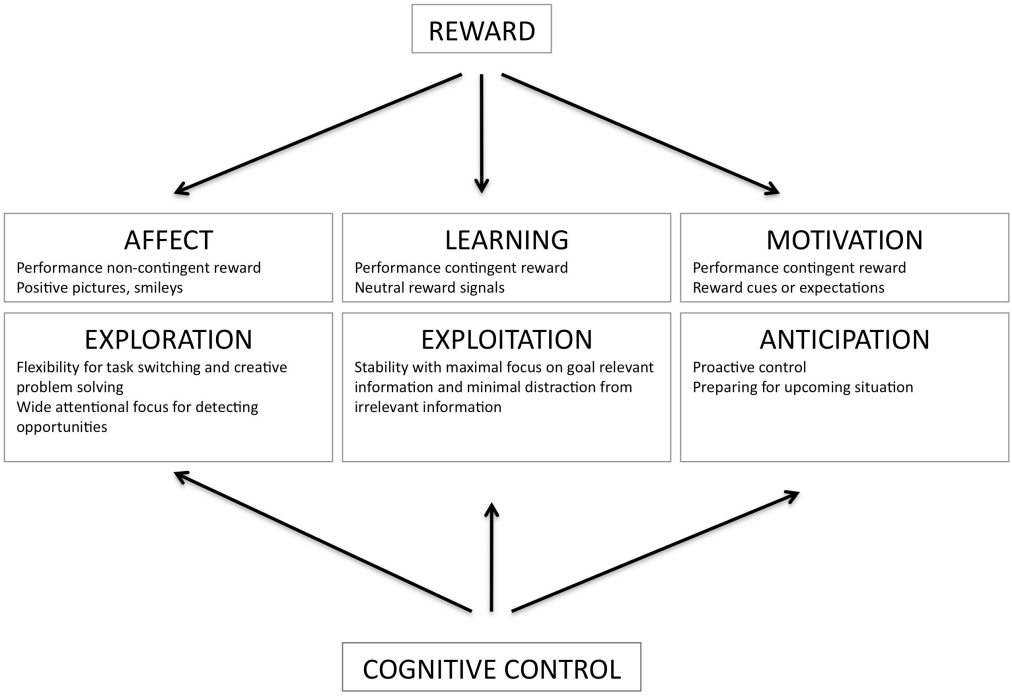

Figure 1. A schematic overview of the different reward components as identified by Berridge and Robinson (2003) with their associated cognitive control behavior.

The hedonic effect of reward on cognitive control: exploration

The hedonic aspect of reward signals is so strong that reward is often used as a manipulation for mood induction. The effects of positive affect have been studied and well documented in scores of studies. In a review paper, Ashby, Alice and Turken (1999) already concluded that positive mood increases flexibility on the basis of more than 25 studies demonstrating improved performance in creative problem solving, decision making and fluency tasks. In line with this idea, Dreisbach and Goschke (2004) demonstrated that positive affect, induced by positive pictures, increased flexibility and decreased stability. Similarly, van Steenbergen, Band and Hommel (2009) presented smileys as reward signals that were delivered in a response non-contingent manner. Contrary to the neutral trials, trials that followed (random) smileys did not show conflict adaptation – remember that conflict adaptation is aimed at increasing stability (decreasing distractor interference). The same authors demonstrated how positive mood induction reduced conflict adaptation (van Steenbergen, Band, & Hommel, 2010; van Steenbergen, Band, Hommel, Rombouts, & Nieuwenhuis, 2014; see also Kuhbandner & Zehetleitner, 2011). Similarly, when reward was delivered in a non-contingent manner, performance in the AX-CPT dropped (Dreisbach, 2006; but see Chiew & Braver, 2014, who did not replicate this finding). These studies suggest that positive mood indeed increases flexibility at the cost of cognitive stability.

The hedonic aspect of reward signals seems to have a counterproductive side effect as it decreases task focus. Ironically, whereas reward is typically administered as a reinforcer, in the hope that the rewarded behavior will be repeated, the hedonic aspect of reward instead turns people away from the task. Therefore, an important question is how and why this hedonic component, and positive mood more generally, triggers explorative behavior. The conventional explanation is that both exploration and positive affect rely on similar dopaminergic networks (Ashby et al., 1999; although other accounts have stressed the role of norepinephrine in exploration as well; Aston-Jones & Cohen, 2005; Gilzenrat, Nieuwenhuis, Jepma, & Cohen, 2010; Jepma & Nieuwenhuis, 2011). Although this analogy is certainly interesting from a neuroscientific perspective, the answer as to why positive affect increases flexibility remains unanswered. For one, it has been postulated that positive mood activates more mood-related thoughts and therefore results in a wider mindset (Seibert & Ellis, 1991). However, one can also consider increased flexibility as a cognitive strategy, in search of new opportunities for reward. Perhaps positive mood acts as a trigger that new

rewards are available in the environment. For example, Carver (2003) suggested that positive feelings act as learning signals that inform us that things are going better than necessary. Next, this positive affect causes the agent to coast, drift off, and shift attention or effort to other domains, which opens up the possibility for detecting new opportunities or satisfying other goals. A similar 'reversed' explanation has been put forward for the association between overall happiness and success (in marriage, job, sports,…). While success obviously makes people happy, happiness engenders success because positive mood makes people also approach goals (Lyubomirsky, King & Diener, 2005). The authors state that "people experiencing positive emotions take advantage of their time in this state –free from immediate danger and unmarked by recent loss- to seek new goals that they have not yet attained" (p 804, Lyubomirsky et al., 2005). Therefore, when salient enough, the effect of the hedonic aspect of reward might override the motivational and learning components of reward, thereby signaling a comfortable environment after successful performance (Carver, 2003; Gable & Harmon-Jones, 2011), allowing for a more exploratory mode.

The learning effect of reward on cognitive control: exploitation

When reward is delivered contingent upon participants' performance by means of simple reward signals (e.g., abstract cues), the hedonic effect of reward is minimized and the learning effect maximized. As both components have opposing effects on cognitive control in our conceptual model, small experimental variations can lead to large empirical changes. For example, whereas van Steenbergen et al. (2009) observed reduced conflict adaptation following random reward in the form of smiley faces, we observed increased conflict adaptation when delivering neutral reward signals (+1) on 25% of the trials (Braem et al., 2012). In our study, reward was not cued, but presented contingent upon participants' performance as it was never presented following slow or incorrect trials. Both aspects (performance contingency and emotionally neutral signal) were deliberately chosen in order to reduce the affective (performance contingent neutral signal) and motivational (uncued feedback) component, therefore singling out the learning component (see also, Braem et al., 2014; Hickey et al., 2010; Stürmer et al., 2011).

How does reward increase stability? We believe the learning effect of reward is implemented by means of increasing goal-relevant associations as described in the adaptation by binding model of Verguts and Notebaert (2008; 2009). In this reinforcement learning model, a Hebbian learning signal is sent throughout the brain ensuring that goal-relevant (active) representations and connections are being strengthened upon detection of cognitive conflict. This general idea is similar to the century-old law of effect by Edward Thorndike (Thorndike, 1911) stating that responses to a situation that are closely followed by rewarding stimuli are more likely to reoccur when this situation presents itself again. The main difference seems to be that increased binding of associations follows reward according to Thorndike (1911), and cognitive conflict according to Verguts and Notebaert (2008; 2009). However, here, in line with recent developments in computational models of performance monitoring (Silvetti, Alexander, Verguts, & Brown, 2013), we tentatively propose that the learning signal put forward in the model of Verguts and Notebaert (2009) could equally likely be a reward or performance prediction error which are both believed to be monitored by one and the same cortical structure: the anterior cingulate cortex (Alexander & Brown, 2011; Silvetti et al., 2013; Silvetti, Seurinck, & Verguts, 2013). Specifically, we suggest that instead of conflict *detection*, conflict *resolution* might be what signals exploitation. The idea that successfully responding to difficult task conditions (conflict resolution) can trigger an intrinsic reward on its own is not new (e.g., Alessandri, Darcheville, Delevoye-Turrell, & Zentall, 2008; Satterthwaite et al., 2012). In fact, a recent observation from our lab tested this for conflict processing specifically (Schouppe et al., in press): participants had to perform a conflict task (Experiment 2) followed by an affective judgment task with positive and negative words. Interestingly, correct performance on incongruent, relative to congruent, trials led to a significant benefit in reaction times on the evaluation of positive, relative to negative, words. This finding was interpreted as reflecting an intrinsic reward signal following the resolution of a difficult task. Now, we suggest that this intrinsic reward signal triggered by resolving cognitive conflict can also be what motivates us in exploiting the associations that led to this successful response (for similar suggestions, see Braem et al., 2012; Schouppe et al., in press).

This idea is consistent with findings that: a) cognitive conflict and errors evoke different cognitive strategies (Notebaert & Verguts, 2011; Stürmer et al., 2011); and b)

conflict adaptation is conditional on the accuracy of the previous response (Van der Borght, Braem, & Notebaert, 2014). Moreover, in demonstrating that reward enhances conflict adaptation, we also showed an absence of conflict adaptation following no-reward (Braem et al., 2012). Consistently, several reward studies have demonstrated that the cognitive control effect of interest often disappears following low or no reward signals (Braem et al., 2014; Hickey et al., 2010; Jiang & Xu, 2014; Muhle-Karbe & Krebs, 2012). These findings further hint at the idea that intrinsic motivation might play an underestimated role in cognitive tasks without reward (Satterthwaite et al., 2012; Schouppe et al., in press; Silvetti, Alexander, Verguts, & Brown, in press), and as we have argued, might even drive some of these typical indices of cognitive control.
Thus, assuming that being correct is its own reward (Satterthwaite et al., 2012) and therefore promotes exploitative cognitive strategies, we argue that the learning component of reward and cognitive exploitation are two sides of the same coin.
In general, a key aspect of our framework is that exploration and exploitation are not competitive modes, but rather two different cognitive control components. This is in contrast to earlier models (Brown, Reynolds and Braver, 2007). It is important to note that the specific task setting will most likely determine whether both strategies are independent or competitive. In gambling tasks for instance, it is clear that exploration (switching to an alternative) is in competition with exploitation (staying with one choice). However, this does not imply that the hedonic effect of reward (increased exploration) is always decreasing task focus (exploitation). The interplay between exploration and exploitation should therefore be further investigated using new paradigms (see guidelines for future research).

The motivational effect of reward on cognitive control: anticipation

The motivational effect of reward can be studied by cueing participants that reward is at stake on the following trial. These cues trigger anticipatory behavior by means of proactive control processes. Depending on what the participants are anticipating proactive control process either increase stability or increase flexibility by means of the mechanisms described above. Padmala and Pessoa (2011), for instance, presented pictures of houses and buildings with the words HOUSE, BLDNG or XXXXX printed over the pictures, creating congruent, incongruent and neutral Stroop-like trials. Trials

started with the presentation of a cue $00 or $20. The high reward cues decreased both interference (incongruent vs neutral) and facilitation (congruent vs neutral).
Krebs and colleagues (2010) used a slightly different approach and rewarded only a subset of colors in a color Stroop task and observed reduced Stroop interference for rewarded colors. Using this approach, reward information and task information are being presented simultaneously and it is still discussed whether this also reflects (fast) anticipatory control. However, the contingency between a specific task-relevant stimulus feature (color) and reward might have triggered the learning component as well. Indeed, Krebs and colleagues also observed that irrelevant words related to the rewarded colors resulted in greater interference, suggesting increased activation for the rewarded semantic category. In this volume, Krebs, Hopf, and Böhler argue in favor of distinguishing cue-based and feature- based anticipatory behavior. Although they recognize that more research is required, they tentatively suggest that cue-based processes are more proactive in nature, while feature-based processes are more reactive in nature.
The above-mentioned results suggest that reward prospect strengthened goal relevant processes. On the basis of these (and other studies demonstrating similar effects), we would conclude that the motivational effect of reward increases stability. However, there is also support for the idea that reward prospect increases flexibility (decreased task-switch cost; Kleinsorge & Rinkenauer, 2012). Moreover, in a recent study Aarts and colleagues (2014) demonstrated that individual differences in levels of dopamine modulated the effect of a promised reward. To this end, a spatial Stroop task was administered where each trial was preceded by a first cue that indicated whether high (15 dollar cents) or low reward (1 dollar cent) could be obtained, and a second cue that either indicated congruency identity (informative) or not (uninformative). Reward was delivered in a response-contingent manner, that is, only for fast and correct answers. There was no overall effect of reward in this task, but the effect of promised reward depended on individual dopamine-synthesis capacity. For participants with higher dopamine-synthesis capacity, the Stroop effect following uninformative cues, but not following informative cues, was increased in high reward trials. The authors propose that for participants with high dopamine-synthesis capacity, the prospect of high reward might ‘overdose’ the dopaminergic system leading to poorer rather than better performance. This dopamine overdose explanation has also been used to explain some

of the unexpected findings of dopamine medication in patients with Parkinson's disease (e.g., Cools & D'Esposito, 2011; Duthoo et al., 2013).

Determining factors

We are aware that our conceptual framework is difficult to falsify. One of the challenges is to predict which component(s) will be activated by the reward signal and hence to predict the specific effect of reward on cognitive control accordingly. As systematic comparisons disentangling different factors of reward (Braem et al., 2013; Chiew and Braver, 2014; Fröber and Dreisbach, 2014) are still relatively scarce, there is room and need for dedicated work disentangling these different components of reward (for similar conclusions, see Braver et al., 2014; Chiew & Braver, 2011; Dreisbach & Fischer, 2012). We identified two important factors that determine the effect of reward on control: *reward signal* (reward saliency and stimulus duration) and *reward schedule* (cue presence and performance contingency), which we will elaborate on below.

Reward signal: reward saliency and stimulus duration

Consider the following analogy: Imagine you are playing pinball at the arcade. The main goal is to keep the steel ball away from the drain by using two hand-controlled "flippers" to gather as many points as possible. You can experience your gained points as reward signals narrowing your focus and helping you to concentrate on the game. However, secondary objectives and bonus missions can maximize your score even faster. Achieving those bonus missions or breaking a record, often indicated by a victory song or flickering lights, will get you even more excited, up to the point that this might bring you in a positive mood which will broaden your focus, and increase distractibility. Similarly, abstract reward signals indicating small monetary gains often help us focusing on the task at hand (Braem et al., 2012; Jiang & Xu, 2014; Stürmer et al., 2011), while more salient reward signals such as positive pictures or smiley faces can induce a positive mood and exploratory focus, counteracting task focus (e.g., Braem et al., 2013; van Steenbergen et al., 2009, 2012), but facilitating task switching (Dreisbach & Goschke, 2004).

This dissociation does not necessarily constitute a dichotomy in reward signal type. Instead, it could also represent both ends of a continuum, where the more salient or affective a reward signal becomes, the more the hedonic component will be activated, and the more it will bring the subject into a positive mood, setting the stage for an exploratory mode of cognitive control. When, on the contrary, the reinforcement signals are more basic, merely providing somebody with performance feedback, these signals will only be used to strengthen information processing associations. Interestingly, in a recent review, Bijleveld, Custers and Aarts (2012) suggested that rewards can be processed on different levels. When rewards are presented only briefly, or time does not permit a full processing of the reward signal, rewards are only processed in a rudimentary form, quickly updating task associations and facilitating task performance. However, when rewards can be processed more fully, more strategic decisions can be made and the effect on performance can then diverge from those of initial reward processing. We believe this framework can also apply to the above-described dissociation. When time is short and reward signals are basic (Braem et al., 2012; Stürmer et al., 2011), rewards mainly activate the learning component and result in a quick reinforcement of the ongoing learning processes. However, when the inter-trial interval is prolonged (e.g., Braem et al., 2013), and rewards are more salient (e.g., Braem et al., 2013; van Steenbergen et al., 2009; 2012), reward activates the hedonic component and promotes an exploratory mode, helping at counteracting the conflict-induced strengthening of associations that are disadvantageous for task-switching. However, systematic comparisons are necessary to test these differences in reward signal type. Fröber and Dreisbach (2014) and Chiew and Braver (2014) recently set up such studies where they aimed at disentangling the motivational from the hedonic component of reward in the AX-CPT task. The AX-CPT task lends itself well to the testing of proactive control (relative to reactive control). Both studies demonstrated that performance-contingent reward cues led to an increase in proactive control. A condition with tightly matched hedonic stimuli (non-contingent positive pictures) either led to a smaller increase in proactive control (Chiew & Braver, 2014) or a reduction in proactive control (Fröber & Dreisbach, 2014).

Reward schedule: cue presence and performance contingency

A first important factor in setting up your reinforcement schedule and testing the impact of reward on cognitive control is whether or not potential reward conditions will be cued or not. It is unlikely that the motivational component of reward or proactive control will be activated when reward is only delivered post-performance. For these reasons, studies like the ones of Padmala and Pessoa (2011), Chiew and Braver (2013; 2014), Fröber and Dreisbach (2014), Kleinsorge and Rinkenauer (2012), and so on, mainly target the motivational component of reward and proactive control, whereas studies like the ones of Braem and colleagues (2012; 2013; in press), Stürmer and colleagues (2011) and van Steenbergen and colleagues (2009; 2012) focus on the learning and/or hedonic aspect of reward, and exploitative and/or explorative behavior, but most likely not the motivational component. This is important to keep in mind, as these studies potentially tap into different mechanisms.

As a second factor, we identify the importance of the factor performance-contingency in predicting which component of reward will be affected. In a first study, we aimed at testing the importance of performance contingency in driving hedonic modulations of cognitive control, we used affective pictures as feedback signals in a performance contingent or non-contingent manner and showed a clear effect of this factor both on brain and behavior (Braem et al., 2013). Although, this modulation generally speaks in favor of our proposition, the specific directions of the effects were somewhat unpredicted. In the contingent condition, flexibility was promoted by positive feedback, while in the non-contingent condition, positive stimuli promoted stability (each time relative to negative stimuli). According to our proposal, especially the non-contingent condition should have loaded the hedonic component and hence increase flexibility, while the contingent condition was expected to load the cognitive component and increase stability. It is, however, important to note that in this study we presented inherently affective pictures (promoting positive affect and, hence, exploration) as reward signals, as well as more arousing negative pictures (which might have driven our modulation as well). Whereas our study focused on reactive control (exploitation more specifically), another study by Fröber and Dreisbach (2014) systematically compared the role of performance contingency in proactive control. There, the authors demonstrated how proactive control is promoted following cues signaling the possibility of receiving a performance-contingent reward, but reduced following cues indicating non-contingent rewards.

Guidelines for future research

We alluded to the idea that the *saliency of the reward signal* might determine to which extent it will induce the hedonic component of reward, assuming that more salient rewards will induce more positive feelings. This would induce an explorative mode of cognitive control (or coasting, see Carver, 2003). Optimally, this hypothesis could be tested in a paradigm where the saliency or magnitude of affective stimuli is parametrically manipulated, best taking into account individual differences in responsiveness to these stimuli. Such a design could potentially demonstrate how reward signals are most efficient in promoting exploitation of the task set, when not too salient (for a similar reasoning on punishment signals, see Braem et al., 2013).
Moreover, we hinted at the idea that *longer reward presentations* might induce more cognitive appraisal processes, resulting in more positive evaluations of the reward signal. Short presentations, on the other hand, only allow for a rudimentary impact on performance, quickly reinforcing whatever led to it. Again, this could be tested by parametrically manipulating the duration of the reward signal presentation and/or the reward-stimulus interval.
Besides varying the reward signal itself, researchers should also engage in comparing *different reinforcement schedules and performance contingencies*. For example, keeping the reward signal type constant, one could contrast its use as a cue signal with that of a performance-contingent feedback signal, promoting anticipatory and exploitative control, respectively.
Finally, in testing the impact of reward on cognitive control, it is important to keep in mind which *cognitive paradigm* is being used. For example, studying the congruency sequence effect naturally puts an emphasis on exploitative strategies (and modulations thereof). Similarly, task-switching studies promote explorative behavior, and the AX-CPT task focuses on anticipatory behavior. A key aspect of our proposal is that exploration and exploitation are not competitive modes, but rather two different cognitive control components. In most tasks, however, exploration is in competition with exploration (e.g., gambling), making it difficult to investigate one component irrespective of the other. One way to overcome this is a task where participants can voluntarily chose which task to perform, a flanker task, a Simon task or a Stroop task, in

which the relevant dimension always remains the same (color). This set up allows separate investigations of exploration (voluntary select another task) and exploitation (focus on task relevant information).

Conclusion

Many research teams are currently investigating the effects of reward on cognitive control. This has led to a substantial increase of interesting studies but not necessarily to our understanding of how reward influences human behavior. Clearly, reward influences information processing in many different ways and subtle differences in design can make huge differences in results. Recently, researchers have recognized this problem (Braver et al., 2014; Chiew and Braver, 2011; Dreisbach & Fischer, 2012) and first studies were set up to identify which experimental factors were crucial in modulating the effects (Braem et al., 2013; Chiew and Braver, 2014; Fröber and Dreisbach, 2014). However, we believe that also a conceptual framework is needed. On the basis of Berridge and Robinson's parsing of reward components, we parsed three cognitive control components and linked each reward component to a control component. First, we argued that the hedonic effect of reward (positive mood) primarily influences the explorative component of control. Specifically, positive mood triggers people to search for opportunities and new rewards. Second, the learning effect of reward promotes the exploitative component of control. In fact, learning via reward and exploitation following successful performance might reflect one and the same process. Third and last, the motivational aspect of reward operates via the anticipatory control component, also called proactive control, which prepares the organism for what is to come.

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